Impact to Space Shuttle Vehicle Trajectory on Day of Launch from change in Low Frequency Winds

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The National Aeronautics and Space Administration's (NASA) Space Shuttle utilizes atmospheric winds on day of launch to develop throttle and steering commands to best optimize vehicle performance while keeping structural loading on the vehicle within limits. The steering commands and resultant trajectory are influenced by both the high and low frequency component of the wind. However, the low frequency component has a greater effect on the ascent design. Change in the low frequency wind content from the time of trajectory design until launch can induce excessive loading on the vehicle. Wind change limits have been derived to protect from launching in an environment where these temporal changes occur. Process of developing wind change limits are discussed followed by an observational study of temporal wind change in low frequency wind profiles at the NASA's Kennedy Space Center area are presented.

Nomenclature

DADS	=	Day-of-Launch Ascent Design System
DRWP	=	Doppler Radar Wind Profiler
KSC	=	Kennedy Space Center
LCC	=	Launch Commit Criteria
LST	=	Local Standard Time
λ	=	Wavelength
NASA	=	National Aeronautics and Space Administration
QC	=	Quality Control
SSP	=	Space Shuttle Program
T	=	Time
UTC	=	Universal Time Coordinate

I. Introduction

THE National Aeronautics and Space Administration's (NASA) Space Shuttle utilizes a two step program to design the vehicle's first stage open loop steering and throttle commands to best optimize vehicle performance. The Day-of-Launch Ascent Design System[1] (DADS) program consists of a three degree-of-freedom routine named SHAPER and a six degree-of-freedom routine named BIASER. SHAPER uses low frequency filtered wind data

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from the day of launch wind to design throttle commands and initial values of the open loop steering commands. BIASER will adjust the SHAPER generated pitch and yaw steering commands using unfiltered wind data to center wind induced alpha and beta spikes. First stage guidance commands are designed at approximately 4.5 hrs prior to launch and validation of the resultant trajectory continues through launch. Temporal change in the low frequency wind component between first stage design and launch has the possibility to invalidate the commands generated by DADS. To address this problem, new wind change limits were developed to protect from launching into an environment where excessive low frequency temporal wind change occurs over this period. The following sections describe the methodology used to determine the wind change boundaries and a study of low frequency temporal wind change in the altitudes between 7,500 and 50,000 ft over Kennedy Space Center (KSC), FL.

II. Derivation of Wind Change Limits

In order to perform this new check, wind change limits had to be developed which define vehicle capability. Winds from a Space Shuttle Program (SSP) certified database of high resolution Jimsphere[2] (100-ft interval) wind profiles were used to develop wind change limits based on shuttle vehicle and loads simulations. Specifically, the 150 wind profile set from February was chosen as this month is generally regarded as the "worst wind month" from a shuttle ascent design perspective. Percentile winds were calculated using the bivariate (in-plane and out-of-plane components)[2] normal distribution of those winds at each 100-ft altitude increment. The smooth percentile winds do not contain all of the frequency content that would be expected on launch day. To remedy this problem, the 150 February winds were filtered using the SHAPER filter in order to save the high-frequency content so it could be added to the smooth statistically generated winds. Examples of statistical wind modifications are shown in Figs. 1 through 3. Figure 1 shows the mean wind and a shift using the normal distribution of the February winds. Figure 2 shows an example wind, the SHAPER filtered wind, and also the resulting high frequency content of the wind. Figure 3 shows the percentile winds with the high frequency content added.

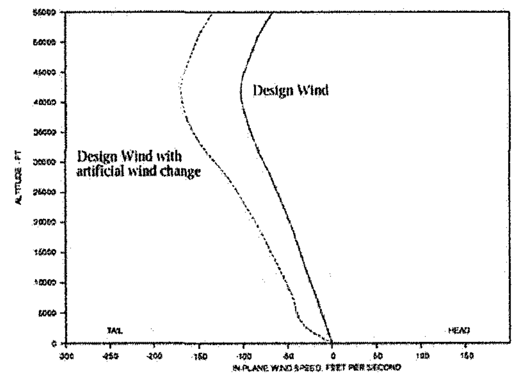


Figure 1. Shifted February mean wind based on distribution of February wind database.

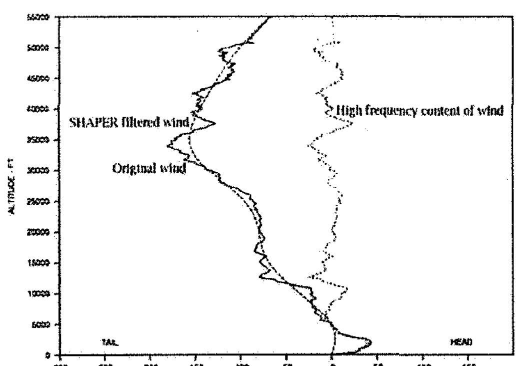


Figure 2. SHAPER filter wind with resulting high frequency wind content.

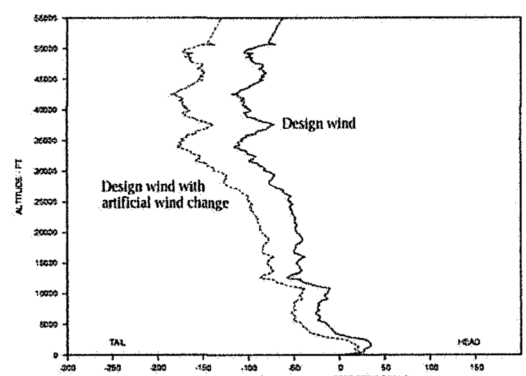


Figure 3. Percentile wind with the high frequency content added.

Initial tests consisted of 150 sets of steering commands that were designed with the mean wind plus the high frequency content. Trajectory and loads simulations were run with more extreme percentile winds (with high frequency content added). If all of the 150 winds passed every trajectory and loads constraints, another set of simulations were performed with more wind change. Otherwise, another set of simulations were performed with less wind change. This process was repeated until the limiting case was found. Wind change was evaluated in this way toward the headwind, tailwind, each side of crosswind and quartering winds. The results showed that the quartering

winds were limited by the pure crosswind component, therefore the resulting limits are for headwind, tailwind, and left and right crosswind. A limitation of this procedure is that the statistical wind change begins to decrease above approximately 40,000 ft in altitude. From experience, the space shuttle is able to accommodate more wind change at these altitudes. The actual wind profiles were modified by keeping the wind change at higher altitudes equal to the wind change at 40,000 ft. This is clear in the resultant wind change limits shown in Fig. 4 (acceptable in-plane wind change) and Fig. 5 (acceptable out-of-plane wind change).

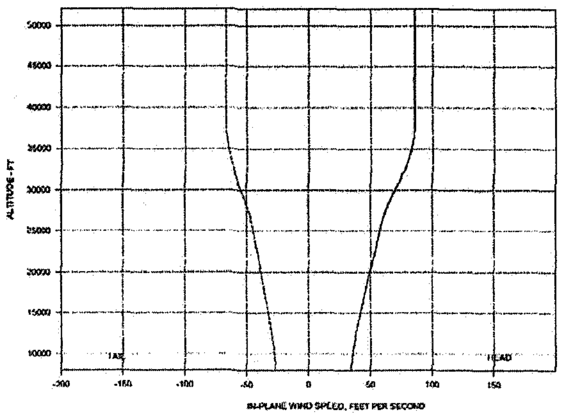


Figure 4. In-Plane wind change limits.

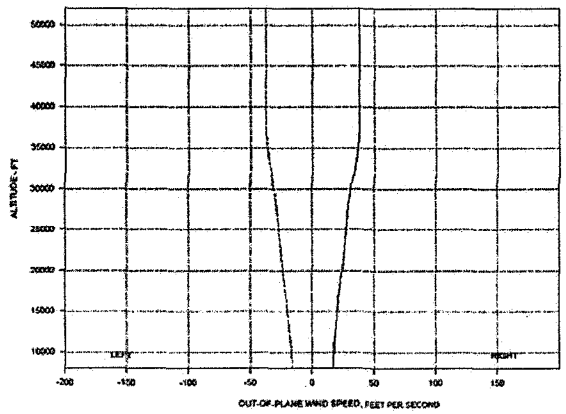


Figure 5. Out-of-Plane wind change limits.

These wind change limits are intended to protect for long wavelength wind change that invalidates the design process. To perform a check against these limits, the winds in question must be filtered using the SHAPER filter and then subtracted. The resulting filtered difference is compared to the limits shown in Figs. 4 and 5. However, because of the way these wind change limits were developed (using a shift of the entire wind profile) a very slight violation of the limits should not be cause for stopping a launch. A minimum altitude interval had to be defined which determined how much filtered wind change was significant enough to alter the trajectory in such a way that the steering command design should be considered invalid. To accomplish this, wind features of various sizes were applied to the 150 February wind profiles and the results were analyzed. To help visualize the effect of wind change on trajectory parameters, the following three figures demonstrate how an increase in the altitude interval of an out-of-plane wind feature affects sideslip angle, beta. The plots show the comparison in beta versus Mach for a wind with and without an artificially introduced wind feature. Figure 6 shows a wind feature that ramped in and then back out over 3,000 ft each. The response in beta in the second wind is clearly seen. Figure 7 shows a wind feature that ramps in over 3,000 ft, maintains a constant velocity for 7,500 ft, and then ramps back out over 3,000 ft. Figure 8 depicts the same type of wind feature, but with the constant velocity held for 15,000 ft.

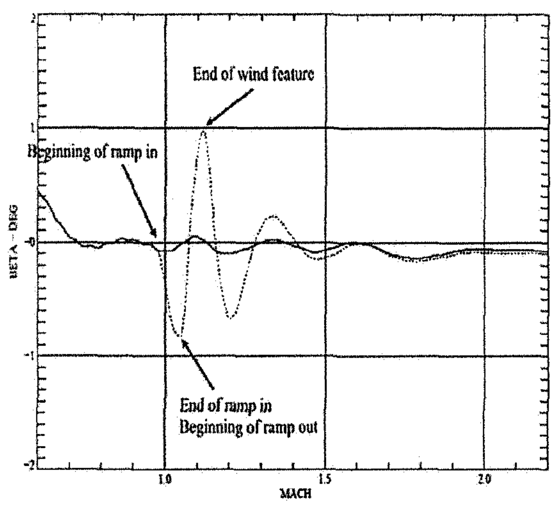
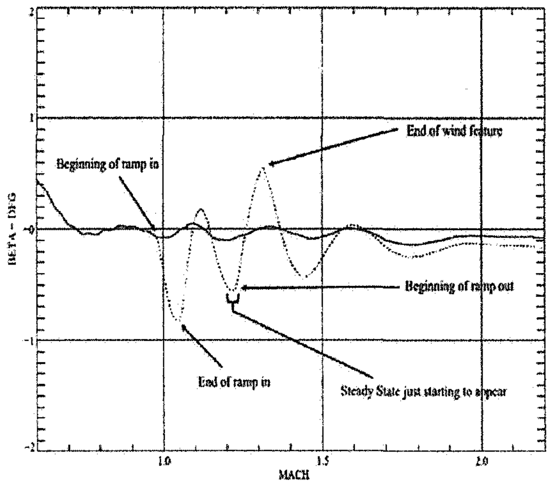


Figure 6. Response to sideslip angle, beta from wind feature ramped in and then out over 3,000 ft.

In all cases, a transient response to the wind feature is present. In the last case, a steady state "error" from stale steering commands is clearly seen. This steady state response just begins to appear in the second plot. Based on these result as well as careful scrutiny of many sizes and types of artificially induced wind features into the 150 February wind database, the minimum altitude interval that would cause steering commands to begin to be invalid was defined as 7,500 ft. Therefore, the space shuttle will possibly be in danger if the proposed wind change limits



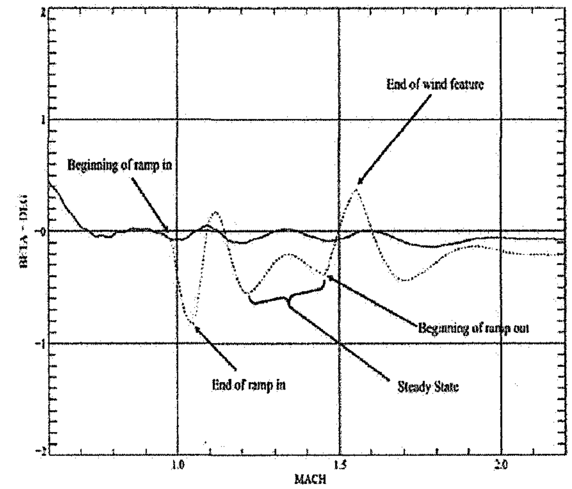


Figure 7. Response to sideslip angle, beta from wind feature ramped in over 3,000 ft held constant over 7,500 ft and ramped out over 3,000 ft.

Figure 8. Response to sideslip angle, beta from wind feature ramped in over 3,000 ft held constant over 15,000 ft and ramped out over 3,000 ft.

are violated for a minimum altitude interval of 7500 ft and the launch should be called a NO-GO for upper level winds. The basis of this decision is that the current measured winds have invalided the ascent design performed 4.5 hrs before launch.

III. Assessment of Wind Change Limits

As an analysis of the wind change redlines derived from the February 150 per month wind database, several wind change databases were evaluated against the derived wind change limits to determine if the limits derived based on vehicle capability were representative of wind change in the altitudes from 3-15 km over central Florida. As mentioned previously, the month of February is considered the "worst wind month" for shuttle ascent design because the winds over central Florida in the winter season are typically the strongest and are susceptible to large temporal variability[3]. Three databases selected to assess the wind change limits contained measurements made over time periods from 2.0 to 4.0 hours. The first database consists of 1,000 high resolution Jimsphere wind pairs with a spatial separation between 2.0 and 3.5-hrs. The second database was constructed entirely of KSC 50-MHz Doppler Radar Wind Profiler (DRWP) data while the third database consists of recent observations using a combination of the KSC 50-MHz DRWP and rawinsonde balloon profiles.

A database of Jimsphere balloon wind profile pairs over central Florida contains wind profiles separated in time at 2.0 and 3.5 hrs. Each wind profile consists of wind speed and direction with a spatial resolution of 25 m from the surface to 20 km. Measurements were made during all seasons over a non-consecutive 40 year period (1965-2005). Each pair is separated by at least 24-hrs in order to maintain temporal independence among the wind pairs. This is a SSP certified database that has been used in multiple vehicle sensitivity studies.

The KSC 50-MHz DRWP database contains profiles collected in five minute intervals over a period of 117 days from 29 September 1995 through 26 March 1996. This database was used in previous studies of temporal wind variability over central Florida[3]. Each DRWP profile contains data evenly spaced at 150 m intervals from 2-18 km. The DRWP was quality controlled to remove spurious noise which could cause erroneous results[3].

The daily observations began in mid-November 2005 and ended in late May 2006. One observation period per day was used to build the database. Data from the KSC 50-MHz DRWP and rawinsonde data were quality controlled with algorithms used during space launch operations.

A. Methodology

There were two separate assessments of wind change to validate the derived wind change limits. This was necessary because of the spatial resolution of wind measurements in the databases. The 1000 Jimsphere wind pairs database had the required spatial resolution needed by the SHAPER and BIASER algorithms. This allowed for loads and trajectory evaluations on the second wind of the pair to determine if the wind change over the period would invalidate the first stage guidance commands built off of the first wind profile. A limitation of the databases constructed with 50-MHz DRWP data is the inability to ingest the mismatched spatial separation into BIASER algorithm to evaluate trajectory response to the wind change over the period. Therefore, results from assessment of

the Jimsphere pairs database were used as a baseline to compare to the number of violations observed with the other two databases. Out of the 1000 pairs, 0.5% (5 out of 1000) violated the wind change limits. Of those 5 cases, only one resulted in a launch No-Go after running a loads and trajectory simulation with the second wind profile. However, because the 50-MHz DRWP is the only measurement within 45 minutes of launch a loads and trajectory simulation cannot be performed. Therefore, 0.5% was used as a baseline to evaluate the other two datasets.

A 4.0 hr time period was chosen to assess wind change with the other two databases. This is the time period during shuttle day-of-launch operations when wind change assessments are made to ensure that the change in the large scale wind environment has not deviated from the time first stage guidance commands would have been calculated. Wind change limit evaluation consisted of calculating a smoothed wind profile based on the mathematical difference between two SHAPER filtered wind profiles separated by a time ranging from 2.0 to 4.0 hrs and comparing the smoothed wind profile against the wind change redlines. Each calculated profile was compared against the wind change limits for in-plane and out-of-plane components. The test was considered a failure when the violation of the wind change limit occurred when the calculated profile exceeded the wind change limit over a continuous 7,500 ft interval. Calculated profiles where the wind change does not exceed the limits at any altitude are considered a successful test. An additional analysis was performed for each wind change violation case which used the Space Shuttle weather Launch Commit Criteria (LCC) to determine if any weather constraints would have resulted in a launch No-Go. This would indicate that the environment was not suitable for launch due to other atmospheric factors. Cases where LCC violations occurred were not included in the results.

The KSC 50-MHz DRWP database consisted of profiles in 5 min increments. Data were partitioned into unique samples in order to minimize multiple counting of violations and to yield meaningful results from a launch operations perspective. Wind features of a specified wavelength (λ) becomes uncorrelated after time, T, based on the following equation[4,5]:

$$\lambda = 460 * \sqrt{T} \tag{1}$$

From Eq. (1), the portion of the wind with wavelengths of 7,500 ft becomes uncorrelated in approximately 4.5 hrs. Therefore, the database was partitioned into 4.5 hr wind regimes for wind change assessments. This resulted in between five and six wind change assessments per day over the 117 day period for a total of 624 assessments.

The daily observation database was constructed from two wind measurement sources; a rawinsonde balloon profile and the KSC 50-MHz DRWP. Since upper atmospheric winds are not as sensitive to diurnal variability that occur in the atmospheric boundary layer (surface to 2,000 ft), the 4.0 hr observation period occurred between 0600-1000 LST (1100-1500 UTC). The rawinsonde profile represented the wind measurement used for the initial loads calculation. The DRWP collected wind profiles over a two hour period starting two hours after the release of the rawinsonde balloon. The DRWP and rawinsonde data was manually quality controlled (QC) to ensure the data is not corrupted by spurious signal return. Quality control procedures used on day-of-launch for both data sources were applied during the two hour observation period. This resulted in 77 acceptable cases for assessment against the wind change limits.

B. Results

Of the 624 50-MHz DRWP cases, there were 62 violations of the wind change limit over at least 7,500 ft. The majority of the 62 cases were associated with violations of the wind change limits in the out-of-plane wind component. As seen in Fig. 5, out-of-plane wind change limits are more constraining due to the vehicle being more sensitive to winds oriented normal to the flight azimuth. Assessment of SSP weather LCC limit rules in cases of wind change violations resulted in 38 cases where weather LCC violations occurred. Therefore, 24 cases (3.8%) had no additional weather constraints associated with the wind change violations. Most of the weather LCC violations were associated with precipitation, ceiling and cloud cover.

From the 77 daily synoptic observations, there were three cases which had violations of the wind change limit over at least 7,500 ft. All three cases were all associated with violations of the wind change limits in the out-of-plane wind component. Of those three, two cases (2.6%) had no additional weather constraints associated with the wind change violations. Details of the two cases were no additional weather constraints follows.

The first violation occurred on 3 May 2006 in the out-of-plane wind component profile. Mid-level wind speeds between 20-35 kft decreased during the period with little change in the wind direction. Profiles of wind change from the initial wind profile throughout the period are shown in Fig. 9. Positive wind change represents decreasing wind speeds from the initial profile. Change in the wind difference profiles occurred gradually over the period. By the end of the period the wind change profile had exceeded the wind change limit over a 7,500 ft interval between 25-33 kft.

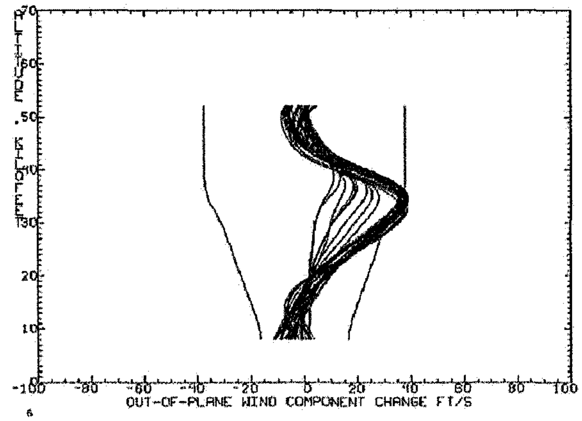


Figure 9. Out-of-Plane wind component change over 4-hour period on 3 May 2006.

A week later, 10 May 2006, mid-level wind speeds increased by ~50 ft/s from 15-30 kft over central Florida during the observation period, Fig. 10. As with the 3 May case, wind direction remained oriented in the out-of-plane component which results in a smaller margin of allowable wind change that could invalidate the I-Load design. Figure 11 shows the wind change over a 3.5 hr period. The wind change exceeding the wind change limit lover 7,500 ft interval occurred over the last hour of the period. By the end of the period wind change had violated the wind change limit over an 11,700 ft interval. A trend observed with all cases assessed was the gradual change in the wind difference profiles over the period and, in the event the wind change violated the wind change limits, the change had occurred over a time period of hours. This is an expected result as changes to the low frequency wind component occur over larger time scales.

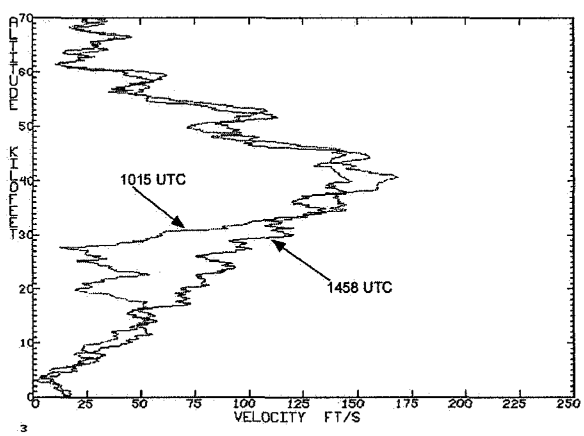


Figure 10. Measure wind velocities on 10 May 2006 between 1015 UTC and 1458 UTC.

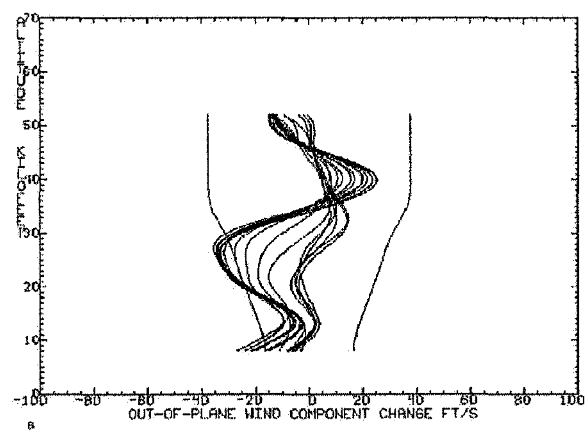


Figure 11. Out-of-Plane wind component change from 1015 to 1345 UTC on 10 May 2006.

IV. Conclusion

Results of wind change redline evaluation from recent observations has shown redlines derived from independent wind data sources were representative of wind change that occurs over the central Florida region. The KSC 50-MHz DRWP database contained 62 cases of wind change redline violations over an altitude greater than 7,500 ft. Recent synoptic observations from KSC had three violations. From an analysis of synoptic and surface conditions, 26 of 65 violation cases (24 from 50-MHz DRWP database and 2 from daily observations) indicated that the violations were not associated with deteriorating atmospheric conditions which would have been unsuitable for launch. The case from 3 May 2006 occurred in an environment where the upper level winds were becoming more benign but increasingly deviating from the I-Load design wind. In the 10 May 2006 case, winds increased over the time period. This is represents an example of the type of environment the limits were designed for in order to protect from launching into during day of launch operations. A similar trend with all the wind change profiles was the change in the wind difference profiles occurred gradually over the time period. Based on these results,

consideration for the variation in atmospheric winds must be accounted for in the initial loads design process in order to best optimize the vehicle's trajectory and ensure from launching into an unsuitable environment.

Acknowledgments

Thanks to Dr. F. Merceret for the KSC 50-MHz DRWP database and to J. David Chapman and the staff at the Cape Canaveral Air Force Station Meteorological Operations Facility for the quality control of the rawinsonde and the 50-MHz DRWP data used in the 2005-2006 observational databases for wind change limit assessment.

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01/10/2007

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Agenda

- Background
- Derivation of Wind Change Limits
- Response of Vehicle to Wind Change
- Assessment of Wind Change Limits
- Summary

Background

- Space Shuttle utilizes a two step program to design vehicle's first stage steering and throttle commands.
- Measured wind data during day-of-launch operations used as input into loads and trajectory algorithms.
- Temporal change in upper level winds has the potential to invalidate the first stage guidance commands.
- Objective of study was to develop wind change limits to protect from launching into an environment where excessive temporal wind change occurs.

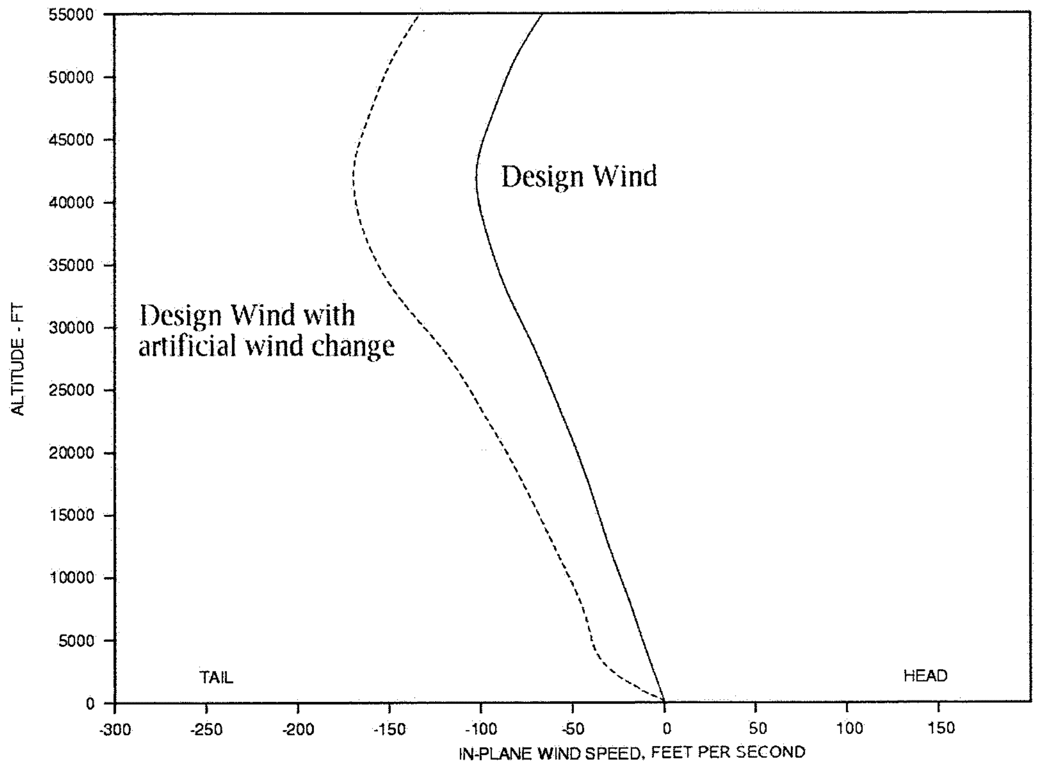
Derivation of Wind Change Limits

- Three step process.
  - Design Initialization-Loads (I-Loads) using the mean wind.
  - Run trajectory / loads simulation using a shifted "percentile wind".
  - Refine guess of percentile until the failure condition is found.

Derivation of Wind Change Limits

- Database of wind profiles from February used to quantify percentile wind.
  - February database regarded as "worst wind month" form a shuttle ascent design perspective.
  - Calculate a mean and standard deviation from the 150 winds at every altitude point (in-plane and out-of-plane), and perform inverse normal calculations to create a "percentile wind".
  - Evaluate wind profile shifts toward the tailwind, headwind, crosswind, and quartering winds.

Derivation of Wind Change Limits

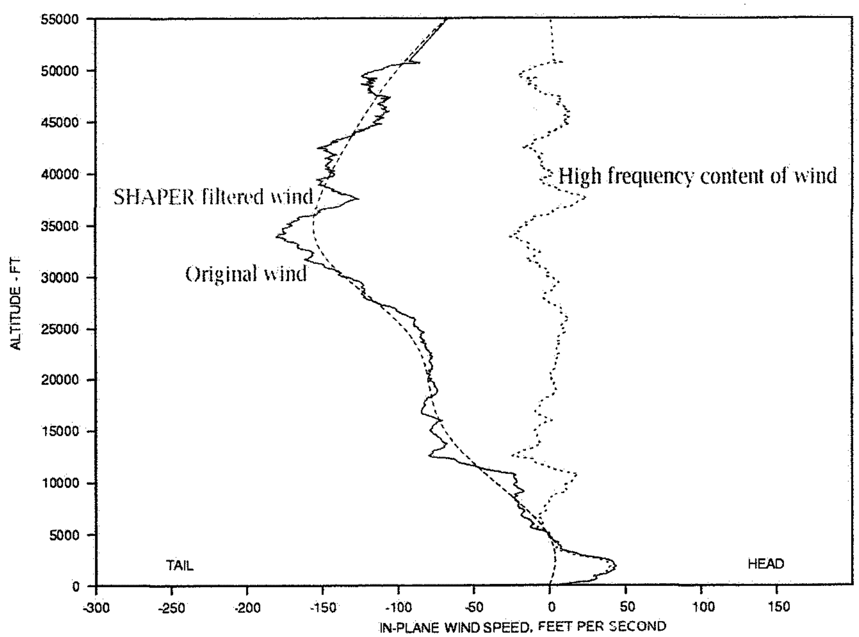


Shifted February mean wind based on distribution of February wind database.

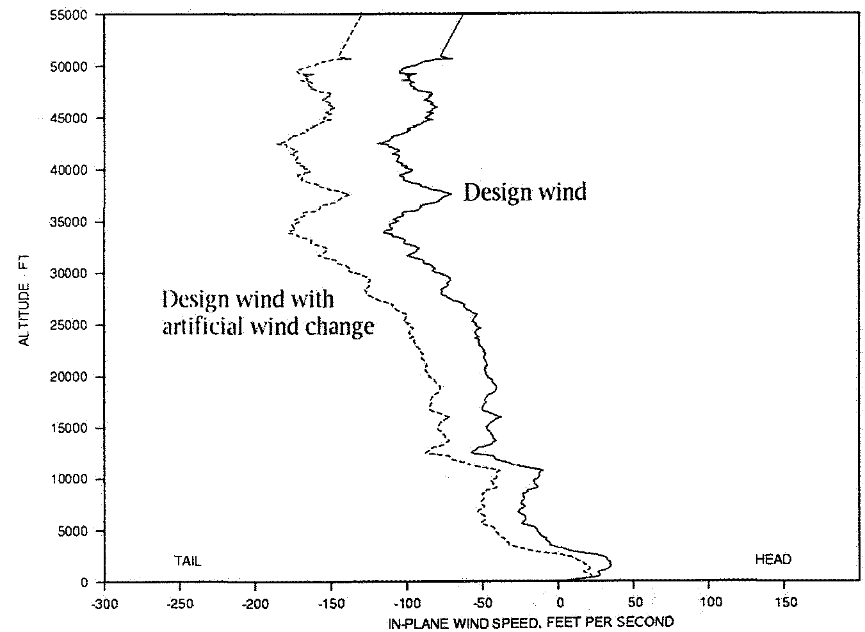
Derivation of Wind Change Limits

- Must account for high-frequency wind content in wind profiles to have a robust trajectory and loads simulation.
- Use high frequency content in February wind database.
  - Use the SHAPER filter to strip the high frequency content from each of the 150 winds.
    - High Freq. Content = Actual Wind – SHAPER Filtered Wind
  - Add the high frequency content from each of the wind profiles onto the mean wind and calculate unique I-Loads.
  - Add the same high frequency content onto the percentile wind being tested and run trajectory / loads simulation using I-Loads designed around the mean wind.

Derivation of Wind Change Limits



SHAPER filter wind with resulting high frequency wind content.

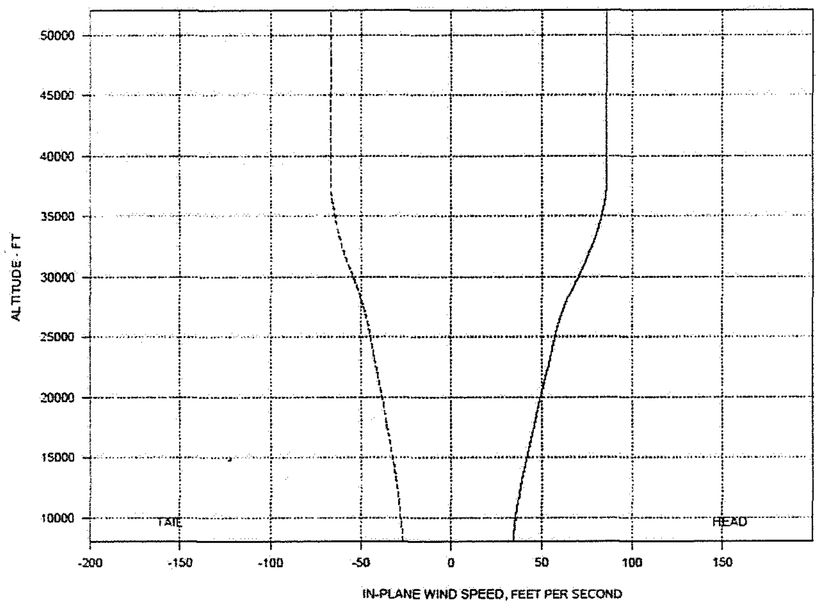


Percentile wind with the high frequency content added.

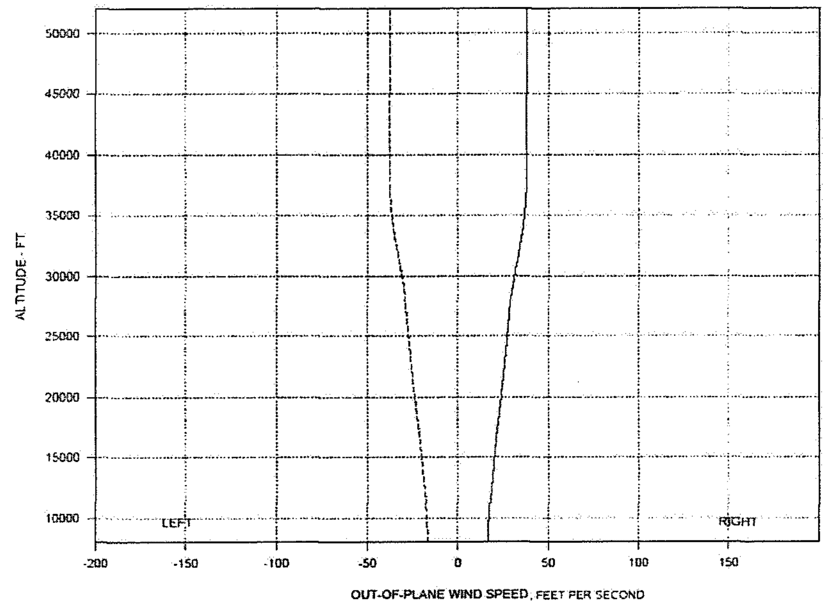
Derivation of Wind Change Limits

- Sets of steering commands designed with the mean wind plus high frequency content.
- Ran trajectory and loads simulations with more extreme percentile winds with high frequency content added.
- Evaluated results against trajectory and loads constraints.
- Iterative process until the limiting case was found.
- Resulting limits are for head/tail wind and left/right crosswind.

Derivation of Wind Change Limits



In-Plane wind change limits.



Out-of-Plane wind change limits.

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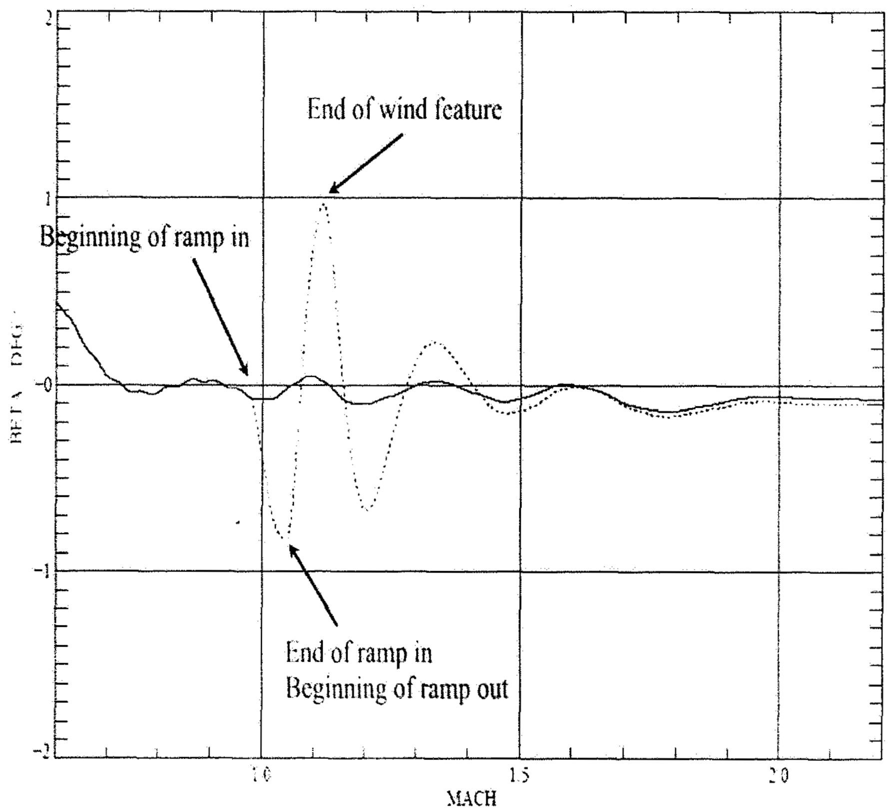
Vehicle Response to Wind Change

- Wind Change Limits are to protect for long wavelength wind change that could invalidate the design process.
- Vehicle response not sensitive to slight violations of the wind change limits.
- A minimum altitude interval had to be defined to determine how much filtered wind change was significant enough to alter the trajectory in such a way that the steering command design should be considered invalid.

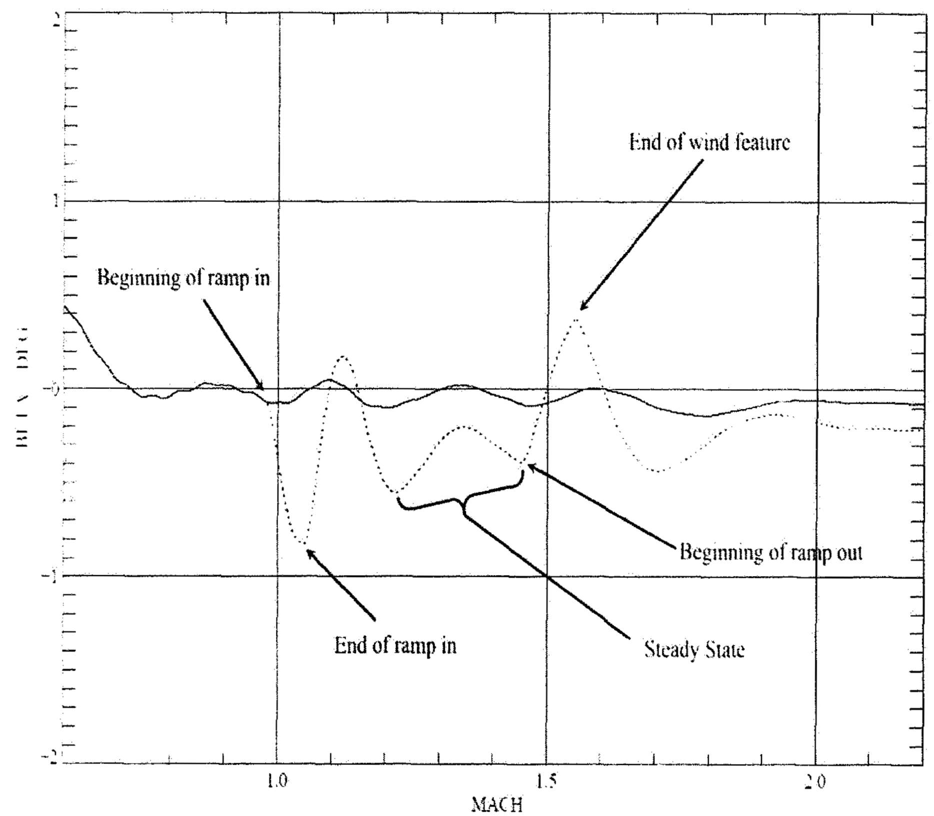
Vehicle Response to Wind Change

- Wind features of various wavelengths were applied to wind profiles to determine response on trajectory parameters (alpha/beta).
- Visual inspection of changes in trajectory parameters were used to determine the minimum altitude interval between a transient response and a “steady-state” response.
- Following plots show how varying altitude interval of out-of-plane wind feature impacts sideslip angle, beta.

Vehicle Response to Wind Change

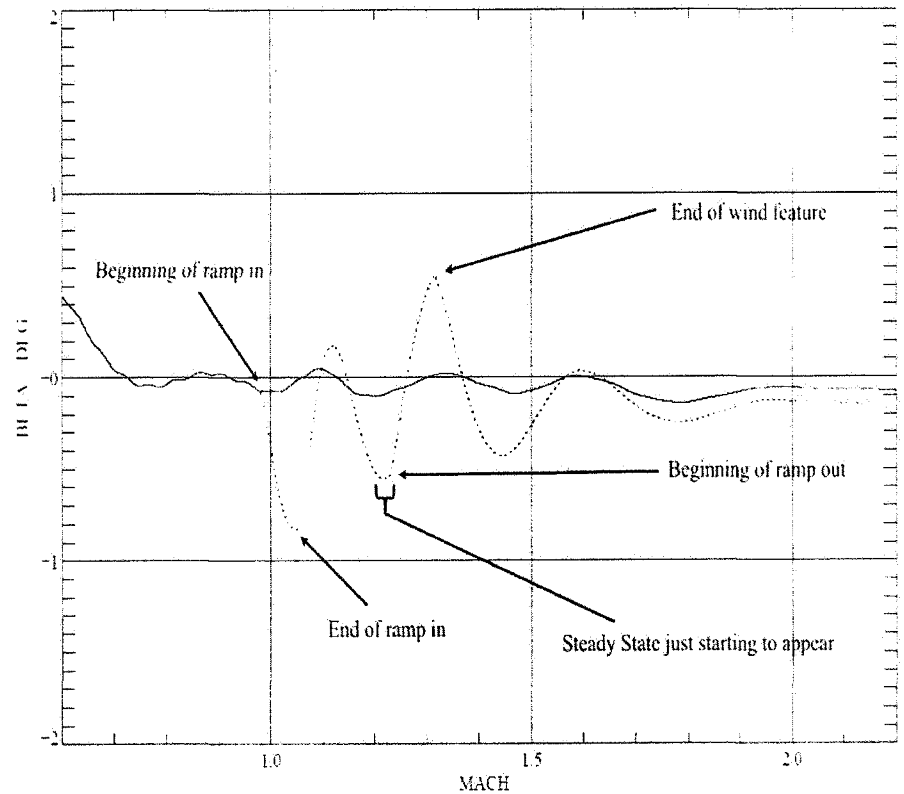


Response to sideslip angle, beta, from wind feature ramped in and out over 3,000 ft.



Response to sideslip angle, beta, from wind feature ramped in over 3,000 ft, held constant over 15,000 ft and ramped out over 3,000 ft.

Vehicle Response to Wind Change



Response to sideslip angle, beta, from wind feature ramped in over 3,000 ft, held constant over 7,500 ft and ramped out over 3,000 ft.

Vehicle Response to Wind Change

- Based on results, if the wind change limits are exceeded over a continuous interval of at least 7,500 ft the steering commands should be considered invalid.
- Criteria used as the basis for assessment of wind change limits in following section.

Assessment of Wind Change Limits

- Analysis of derived wind change limits against observations to determine if wind change limits bases on vehicle capability are representative of wind change over central Florida.
- Independent assessment of wind change limits using three databases containing wind pairs separated in time between 2.0 and 4.5 hours.
  - High Resolution balloon (Jimsphere) wind pairs database.
  - Database from Kennedy Space Center's (KSC) 50-MHz Doppler Radar Wind Profiler (DRWP).
  - "Daily Observational" database consisting of KSC 50-MHz DRWP and rawinsonde balloon profiles.
- Separated assessments based on spatial resolution of the wind measurements in databases.

Assessment of Wind Change Limits

- High resolution wind measurement have the required spatial resolution (25 m) used in trajectory and loads algorithms.
  - Allowed for a full loads and trajectory evaluation of the second wind pair to determine if the wind change would invalidate first stage guidance commands built off of the first pair.
  - 1000 independent pairs with a spatial resolution of either 2.0-hrs or 3.5-hrs.
- Out of 1000 pairs, 5 (0.5%) violated the wind change limits.
  - 1 of the 5 resulted in a launch NOGO after running a loads and trajectory simulation.
  - However, on day-of-launch operations the 50-MHz DRWP is the only source within 45-min of launch and a loads and trajectory simulation cannot be performed.
- Therefore, 0.5% was used as a baseline to evaluate the other databases.

Assessment of Wind Change Limits

- Assessed wind change over 4.5 hr period with 50-MHz DRWP and "daily observational" database.
- Used SHAPER filter to generate smoothed wind profiles.
- Calculated difference between smoothed wind profiles and compared resultant profile to in-plane and out-of-plane wind change limits.
  - Pass; when wind change does not exceed the limits at any altitude.
  - Fail; when wind change exceed limits over a continuous 7,500 ft interval.
  - In a failure case, assessed surface weather conditions to determine if any shuttle launch commit criteria (LCC) weather constraints were violated. In the event of a LCC violation, the case was not included in the results.

Assessment of Wind Change Limits

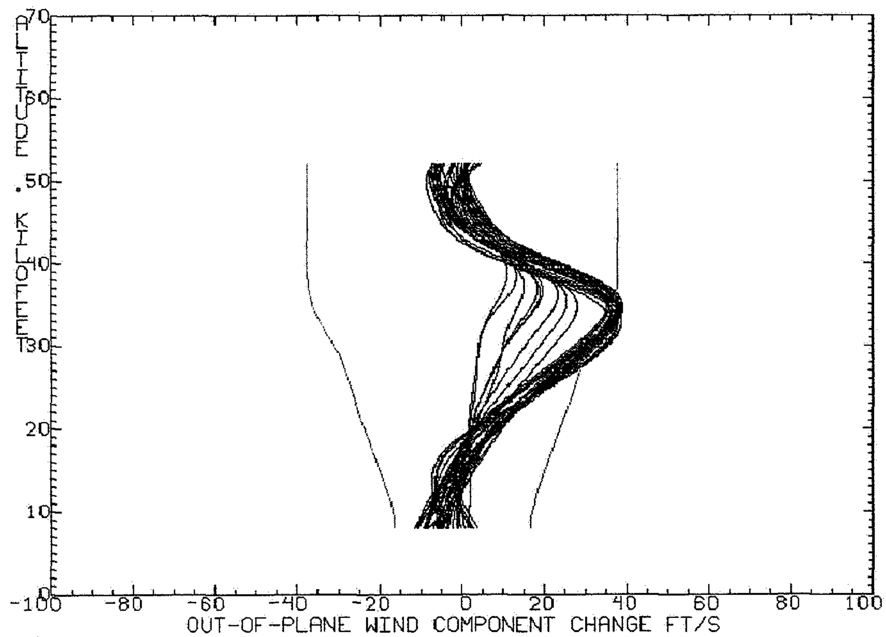
- KSC 50-MHz Doppler Radar Wind Profiler (DRWP) database.
  - Period of Record: 9 Sept. 1995 to 26 Mar. 1996
  - 117 days of available data.
- Partitioned data into 4.5 hour wind "regimes".
  - Timescale where the portions of the wind with wavelengths of 7500 ft or smaller are uncorrelated.
- Wind Change Limit violations occurred in 62 of 624 wind profiles; of those 62, 38 were associated with weather LCC violations resulting in 24 violations solely associated with Wind Change Limit violation (3.8%).
  - Mostly occurred in the out-of-plane wind component.
  - Weather Launch Commit Criteria (LCC) violations were mostly associated with Precipitation, Ceiling and Cloud Cover.

Assessment of Wind Change Limits

- Utilized morning (~1100 UTC) Automated Meteorological Profiling System Low Resolution Flight Element (AMPS LRFE) coupled with 50-MHz DRWP from Eastern Range (ER) complex.
  - Period of Record: 15 Nov. 2005 to 22 May 2006.
  - 50-MHz DRWP data is manually quality controlled.
    - Removal of "Side-lobe" interference.
    - Editing of "first-guess" file to remove unrealistic data.
- Resulted in 77 "daily observational" cases.
- Three cases of wind change limit violations, two of which had no weather LCC violations (2.6%).

Assessment of Wind Change Limits

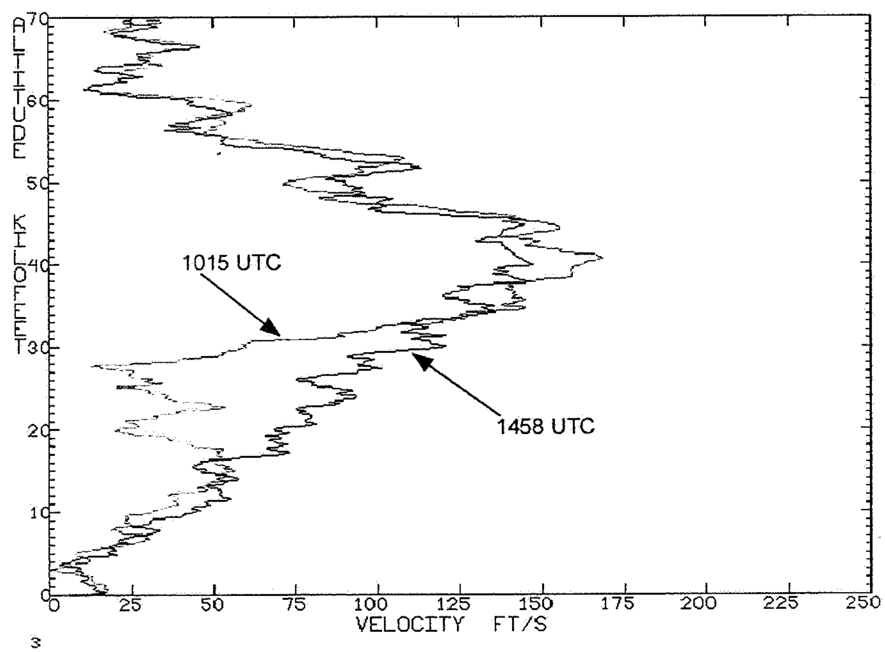
- On 3 May 2006, wind velocities in the 20-35kft region decreased during the period from 1530-2006 UTC.
- Change in the wind difference profiles occurred gradually over period.
- By 1952 UTC, the wind change limits were exceeded over 7500 ft.

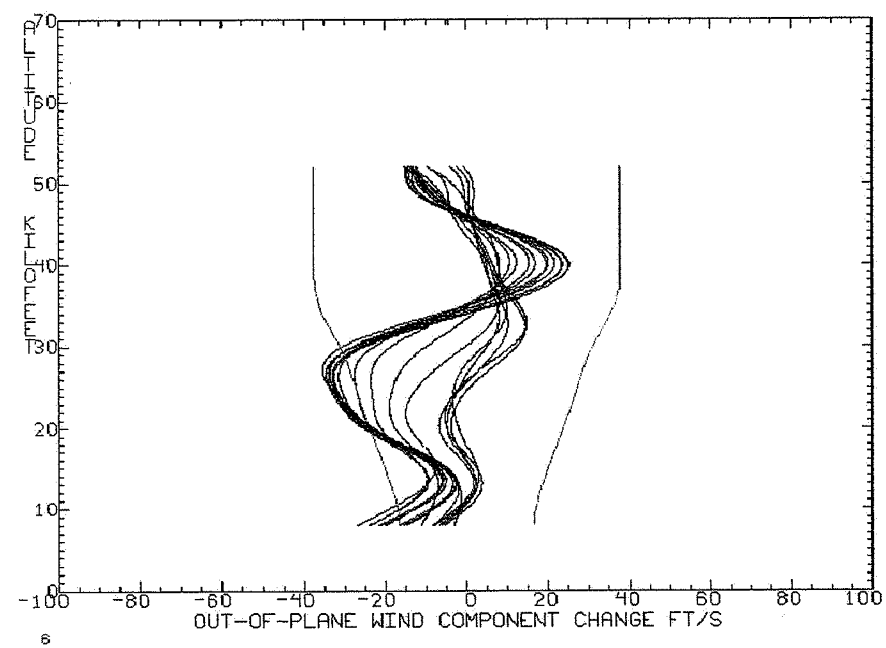


Out of Plane wind component change over 4.5 hr period on 3 May 2006.

Assessment of Wind Change Limits

- On 10 May 2006, wind velocities in the 15-30 kft region increased ~50 ft/s over 4 hour period with little change in wind direction.
- Violations of the wind change limits in the out-of-plane wind component over 7500 ft began with the 1315 UTC 50-MHz DRWP and continued through 1345 UTC (bottom right).





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Summary

- Wind change limits have been derived based on space shuttle vehicle capability.
- Evaluation of wind change limits against independent data sources has shown that the wind change limits are representative of wind change that occurs over the central Florida region.
  - Violations in the KSC 50-MHz DRWP database occurred in 24 of 624 cases (3.8%).
  - Violations from recent ER observations occurred in 2 of 77 cases (2.6%).
- Variation in atmospheric winds must be accounted for in the initial loads design process in order to best optimize the vehicle's trajectory and ensure from launching into an unsuitable environment.

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